

Scenario and Multiple Criteria Decision Analysis for Energy and Environmental Security of Military and Industrial Installations

Christopher W Karvetski,[†] James H Lambert,[†] and Igor Linkov^{‡,*}

[†]Center for Risk Management of Engineering Systems, University of Virginia Charlottesville, Virginia, USA,

[‡]U.S. Army Engineer Research and Development Center Waterways Experiment Station 3909 Halls Ferry Road Vicksburg, Mississippi, USA,

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ABSTRACT

Military and industrial facilities need secure and reliable power generation. Grid outages can result in cascading infrastructure failures as well as security breaches and should be avoided. Adding redundancy and increasing reliability can require additional environmental, financial, logistical, and other considerations and resources. Uncertain scenarios consisting of emergent environmental conditions, regulatory changes, growth of regional energy demands, and other concerns result in further complications. Decisions on selecting energy alternatives are made on an ad hoc basis. The present work integrates scenario analysis and multiple criteria decision analysis (MCDA) to identify combinations of impactful emergent conditions and to perform a preliminary benefits analysis of energy and environmental security investments for industrial and military installations. Application of a traditional MCDA approach would require significant stakeholder elicitation under multiple uncertain scenarios. The approach proposed in this study develops and iteratively adjusts a scoring function for investment alternatives to find the scenarios with the most significant impacts on installation security. A robust prioritization of investment alternatives can be achieved by integrating stakeholder preferences and focusing modeling and decision-analytical tools on a few key emergent conditions and scenarios. The approach is described and demonstrated for a campus of several dozen interconnected industrial buildings within a major installation. Integr Environ Assess Manag 2011;7:228–236. © 2010 SETAC

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INTRODUCTION

Grid outages threaten to result in cascading failures, loss of productivity, and mission degradation at military and industrial installations. An increasingly important objective is the reduction of the number and duration of these outages for buildings supporting critical operations through the development of alternative energy supply and distribution capabilities. Adding redundancy, currently the most widely used practice, requires significant environmental, financial, and logistical considerations and resources. Uncertain future scenarios add complexity to achieving various energy and environmental security goals, such as accomplishing critical mission objectives, integrating multiple fuel sources, reducing energy consumption and disruptions, reducing foreign energy inputs, and using renewable resources (US Army 2005, 2007, 2009; Lambert 2006; Morel and Linkov 2006).

For military or industrial installations, these scenarios include, but are not limited to, future environmental and climatic conditions, regulatory changes, and evolving power demands (Nakićenović 2000; Mintzer et al. 2003; Constantini et al. 2007; World Energy Council 2007; United Nations 2008; Tonn et al. 2009). Scenarios can include local, regional, national, and international conditions or events. For example, international conditions include shifts in the geopolitical power relating to fossil fuels and natural gas that influence the availability and costs of these energies. Conditions at the

installation or facility level include local disruption of energy services caused by commercial energy grid failures, terrorism, weather and climate events, institutional and organizational issues, and changing security requirements. Some conditions or scenarios are factually and scientifically based and mutually agreed upon among stakeholders; others may reflect advocacy positions or specialized points of view.

In management practices, scenario analysis is typically a qualitative exercise (Goodwin and Wright 2001; Swart et al. 2004; Mahmoud et al. 2009; Wright et al. 2009). A defining trait of scenario analysis, which distinguishes scenario analysis from forecasting or predicting, is the absence of probabilities in characterizing possible future uncertain conditions. Scenario analysis emphasizes creativity and communication and formulates unlikely but plausible and consistent, albeit imprecisely specified, vignettes of how the future may unfold. These vignettes seek to characterize system vulnerabilities and opportunities and aid in current and adaptive decision making.

More robust investments strategies can be formulated by grouping a diverse set of future scenarios by their relative impact on decision making (Mason 1998). Multiple criteria decision analysis (MCDA) can provide guidance to organizations making resource allocation decisions under conditions of uncertainty (Keeney 1992; Kleinmuntz 2007). The tools of MCDA can handle the multiple, often competing objectives of technology innovation, financial compliance, energy security, and environmental security. For example, MCDA related to environmental security and environmental management has been described by several investigators (Kiker et al. 2005; Linkov, Satterstrom, Kiker, et al. 2006; Linkov, Satterstrom, Seager, et al. 2006; Linkov et al. 2007). Seager et al. (2007)

* To whom correspondence may be addressed: igor.linkov@usace.army.mil

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describe multiple criteria in dredged sediment management. Linkov et al. (2008) address multi-criteria-based policy making in the face of social and environmental management uncertainties. Lambert and colleagues track emerging scenarios in multiple criteria analysis of large-scale systems over time (Lambert et al. 2005, 2008; Lambert and Sarda 2005).

Multiple criteria decision analysis tools have been effective in selecting energy alternatives in multiple case studies (Chatzimouratidis and Pilavachi 2009a; Nigim et al. 2004). The ELECTRE III method is used for ranking decentralized renewable energy alternatives on insular Greek islands (Papadopoulos and Karagiannidis 2006). Kowalski et al. (2009) discuss applications of participatory multiple criteria analysis with principles of scenario analysis to address complexity for evaluating renewable energy sources in Austria. Two challenges faced here included inconsistent stakeholder participation and describing complex scenarios both in narrative and quantitatively for use in the assessment tool. Loken (2007) discusses different MCDA models, including value measurement models, goal, aspiration, and reference level models, and outranking models, focusing on energy networks with a single energy carrier. Research focused on the use of MCDA models for large-scale integrated energy systems is recommended. These models must be able to deal with multiple decision makers, each possibly having a set of conflicting objectives.

Uncertain future scenarios and associated external uncertainties in the decision setting are important challenges in applying traditional decision analysis tools for prioritizing environmental and energy alternatives. A drawback of traditional MCDA, such as those that use multiattribute value theory (MAVT) models, is that they typically consider only 1 possible future (Comes et al. 2009). A few studies and applications have attempted to link and apply scenario-informed analysis with MCDA for a small set of scenarios (typically 3 or fewer) (Goodwin and Wright 2001; Montibeller et al. 2006; Comes et al. 2009; Wright et al. 2009). The abundance of energy scenario assumptions adds complexity for the integration of MCDA tools for military or industrial facilities as the scope and time domain of energy scenarios are vast. In a large-scale application, Ram et al. (2009) incorporate 12 diverse scenarios to an MCDA framework to evaluate food security options in Trinidad and Tobago by creating an additive value function for each scenario. The elicitation process is entirely replicated for each scenario and repetition and the time demand of the elicitation process are chief complaints of the interviewed decision maker after a few scenarios. Clearly, the inclusion of perspectives for multiple decision makers engaged in a group negotiation can be challenging as well.

New approaches could therefore be useful in the face of a large set of scenarios or multiple stakeholders. With a goal to reduce elicitation burden, the present study integrates MCDA and scenario analysis to 1) prioritize energy-security alternatives and characterize the robustness of the prioritization, and 2) identify the scenarios consisting of local, regional, national, and international conditions that most affect the prioritization of investment alternatives. First, investment portfolios are ranked for a baseline scenario using MCDA methods. Pairwise comparison matrices and the eigenvector approach of the analytic hierarchy process (AHP) are used in this study to generate the scores used to rank the portfolios (Saaty 1990). The preference change of the decision maker is

incrementally evaluated for other scenarios in relation to the baseline scenario. The adjustments in preference translate to adjustments of the pairwise comparison matrices of the AHP. Fewer pairwise comparisons are needed, as only a few past pairwise comparisons are updated for each scenario. The philosophy of modifying a decision model (AHP in this case) rather than completely eliciting all preference information for each scenario is transferable to other MCDA methods, such as value theory (Parnell et al. 1999; Karvetski et al. 2009; 2010; Lambert and Schroeder 2009).

The remainder of the present work is divided into 3 main sections. The following section describes the decision setting for an installation or facility energy manager and details the adjustments to the comparison matrices. A demonstration is next provided. The last section provides discussion and conclusions.

MULTIPLE CRITERIA DECISION SETTING WITH SCENARIO ANALYSIS

Description of the decision setting

The setting consists of energy managers with other supporting stakeholders that must prioritize energy and environmental security alternatives for an interconnected campus of military or industrial buildings that typically rely on the large-scale electrical grid. Grid outages disrupt the operations at the installation and threaten mission execution and security. Depending on the location, these grid outages can range from millisecond blinks to periods of days or months. Key buildings support critical operations on the campus that require energy supplied with considerably higher reliability or quality, but conflicting objectives other than reliability have been noted. The stakeholders have identified alternative investments to provide backup power and islanding capabilities during outages and are concerned with current and future energy and environmental security goals. Examples of alternatives include microgrid technologies, natural gas microturbines, photovoltaic arrays, and diesel generators. Combining an energy technology or source with others creates a portfolio. Typically only particular combinations of energy alternatives are feasible. In practice, considerable technical effort is needed to pair alternatives to construct feasible portfolios, but we do not elaborate on these details in the present analysis. The feasible set of portfolios is defined as $S_p = \{X_1, X_2, \dots, X_w\}$.

The stakeholders evaluate the portfolios on efficiency, availability, cost, emissions, and other performance criteria. In the case of an AHP model, the top overall goal of energy and environmental security is decomposed into a set of performance criteria $Z = \{z_1, \dots, z_m\}$. The interactive eigenvector methods of the AHP generate a baseline set of weights for the criteria using the pairwise comparison matrix defined P_Z . The same methods generate the baseline assessment scores of the portfolios within each criterion using the pairwise comparison matrices for each criterion, defined as

$P_{z1}, \dots, P_{zm}$. As a brief review, the baseline pairwise comparison matrix for the criteria is defined as

$$P_Z = \{p_{ji} | j = 1, \dots, m; i = 1, \dots, m\},$$

where p_{ji} is a level selected by the stakeholders to answer the question: "Thinking only of the baseline scenario, how much is criteria z_j preferred relative to z_i ?" The traditional ordered levels of pairwise preference from least to most (left to right)

are $\{1/9, 1/7, 1/5, 1/3, 1, 3, 5, 7, 9\}$. The pairwise comparison matrix P_{z_k} for an individual criterion z_k is constructed in a similar fashion, but the entry p_{ji} is a level selected by the stakeholders to answer the question: "Thinking only of the baseline scenario, how much is portfolio X_j preferred relative to portfolio X_i with respect to the performance in criterion z_k only?" Synthesizing across all pairwise comparisons gives a composite (baseline) score for ranking the portfolios. The AHP is well documented, and we refer the reader to Saaty (1990) or Belton and Stewart (2002) for more detail.

The next modeling phase investigates the sensitivity of the score of each portfolio to the future scenarios. The aim is to identify the scenarios that are most influential to this prioritization of portfolios. We recognize that future scenarios are typically described by multiple diverse viewpoints from the multiple stakeholders, including regulatory, environmental, social, and others. We therefore define the set of scenarios, labeled as S_C , to be the possible confluence of multiple conditions, where a condition is defined as a single future event or trend that could influence the prioritization of the portfolios. For example, decreased supply of foreign oil is a future energy condition, but this condition could be paired with occurrence of ice storm to create a scenario. The baseline scenario is indexed as s_0 from here on.

The set of scenarios S_C is constructed to provide a plurality of future viewpoints for prioritizing portfolios. A new score used to rank among the portfolios is assigned to each portfolio X_i for each future scenario s_k . This score is again derived using the eigenvector approach of the AHP (Saaty 1990) and synthesizing across the a new pairwise comparison matrix $P_{Z,k}$ for the criteria and the pairwise comparison matrices that compares the portfolios within each criterion, $P_{z1,k}, \dots, P_{zm,k}$. The extra subscript k implies that these comparison matrices are similar to the baseline comparison matrices for the criteria (P_Z) and the comparison of the portfolios within each criterion ($P_{z1}, \dots, P_{zm}$), but the entries of these new matrices can be different to represent the changes in preference induced by scenario s_k . Similar to Ram et al. (2009) and Montibeller et al. (2006), each pairwise comparison matrix for a scenario could be derived separately, but this may not be feasible or efficient, given a larger number of scenarios.

Efficient incorporation of scenarios to the decision model

The approach featured in the present work defines the new comparison matrices under a new scenario as an adjustment of the comparison matrices from the baseline scenario. When the assessment is supplemented with the scenarios of S_C , the objective of deriving the baseline comparison matrix for the criteria $P_{Z,k}$ for each scenario $s_k \in S_C$ reduces to changing the baseline pairwise preference relations in the pairwise comparison matrix. The adjustments are defined for different intensities of preference increase or decrease. Mathematically, this implies that the adjustments are prescribed by a well-defined adjustment function h . For scenario s_k , we have

$$P_{Z,k} = h(I_k, P_Z)$$

and, if necessary,

$$P_{zj,k} = h(I_k, P_{zj}) \text{ for } j = 1, \dots, m.$$

Input I_k represents additional input reflecting preference shifts induced by scenario s_k as compared with the baseline scenario.

With $s_k \in S_C$, the stakeholders may increase the preference levels of some criteria among the others while possibly decreasing preferences levels of other criteria. This additional information is represented mathematically as I_k and is input to the adjustment function h along with the baseline comparison matrix. For example, if it is assumed that gas and oil are available and cost effective, less relevance or importance may be placed on the performance criterion concerned with reducing these energy sources. We describe a systematic and natural approach to adjusting the preferences, admitting that others may be equally acceptable.

For a scenario s_k , the shift in preference for a criterion z_j over the other criteria (in comparison with the baseline pairwise preferences) is defined as $i_{j,k}$. This input is restricted to be a major increase, minor increase, no change, minor decrease, or major decrease in preference. The additional information I_k for the criteria is thus defined as the vector

$$I_k = [i_{1,k}, \dots, i_{m,k}].$$

Input component $i_{j,k}$ answers the question, "Under scenario s_k , is criterion z_j more or less preferred or important (in comparison to the other criteria) than in under the baseline scenario, and if so, what is the extent of this change?"

With reference to the baseline pairwise comparison matrix P_Z , a major increase in preference of criterion z_j improves the preference of z_j over all other criteria by 2 preference levels for the new pairwise comparison matrix $P_{Z,k}$. That is, p_{ji} improves by 2 preference levels for all $i \neq j$ (1 becomes 5, $1/3$ becomes 3, and so forth), and p_{ij} is updated as the reciprocal of the new preference level value. A major decrease in preference of criterion z_j lessens the preference of z_j over all other criteria by 2 levels. A minor increase in preference of criterion z_j improves the preference of z_j over all other criteria by 1 level. A minor decrease in preference of criterion z_j lessens the preference of z_j over all other criteria by 1 level. No preference change does not require a shift of level. Some scenarios require multiple shifts for the pairwise comparison entries of multiple criteria. The ordering of multiple shifts does not affect the derived entries. This implies a unique pairwise comparison matrix for the performance criteria represents each additional scenario.

This approach can be replicated, if necessary, for the pairwise comparison matrices of the portfolios within each criterion, $P_{z1,k}, \dots, P_{zm,k}$. A new score is thus calculated for each scenario s_k for all portfolios. In long-range planning, it is usually most useful and practical to change only the criteria weights that reflect relative importance of the criteria (Parnell et al. 1999). Figure 1 displays a flow diagram of the approach when only the criteria weights change. Dashed rectangles represent the traditional components of MCDA methodology. Solid rectangles represent how emergent conditions are used as inputs in the MCDA methodology. This integration can identify scenarios of emergent conditions that alter how the portfolios are prioritized.

APPLICATION AND DEMONSTRATION

Application of the methodology

This section describes application of the methodology and provides a tutorial demonstration of the approach using AHP. Other interesting case studies and applications using the incremental adjustment approach with a value function

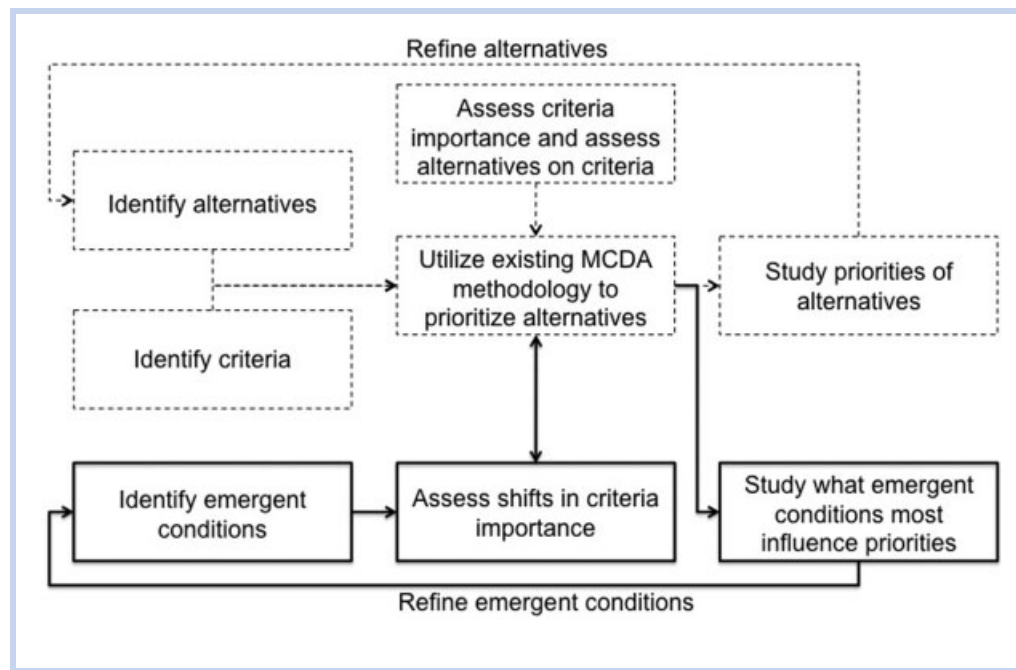


Figure 1. Elements of methodology to identify the most influential emergent conditions for energy and environmental security of an installation or facility. Dashed rectangles and arrows represent the traditional MCDA approach to prioritizing alternatives; solid rectangles and arrows represent how emergent conditions are integrated into the methodology. Supplementing the traditional MCDA approach with emergent conditions can identify what scenarios most affect the prioritization of alternatives.

include multimodal transportation planning (Lambert and Schroeder 2009), infrastructure planning in developing countries (Karvetski et al. 2009), and identification of influential climate scenarios (Karvetski et al. 2010). The current study is unique in introducing and exploring the approach with the AHP.

For transportation agencies, a case study of the approach showed how multimodal transportation investments were vulnerable to different emergent conditions in different geographic regions (Lambert and Schroeder 2009). Specifically, the case study demonstrated that particular regions would be impacted by changing economic conditions and natural hazards, while other regions would be impacted by climate change (sea level) and sociodemographic changes (intensity of population and employment centers).

For the US Army Corps of Engineers (USACE) and the US Agency of International Development (USAID), a demonstration pointed to the vulnerability of infrastructure plans to 2 specific emergent conditions: 1) refugee emigration from Pakistan to Nangarhar Province, and 2) natural disaster (Karvetski et al. 2009). An earthquake occurred in Nangarhar Province concurrently as our partner in USACE was demonstrating the methodology in Nangarhar (Sherzad 2009). Neither of these 2 conditions had been formally addressed in the multistakeholder planning process prior to our involvement.

Demonstration of AHP methodology for energy and environmental security

This demonstration addresses 5 portfolios. We study 5 scenarios, in addition to a baseline scenario. The demonstration supports preliminary engineering and benefits analysis of the portfolios. Consideration of the costs of the portfolios

would further distinguish them from one another. We do not include costs in this demonstration. In a case study, the detailed analyses of cost and schedule of the portfolios might be examined in light of emergent conditions including those identified as influential in our demonstration.

These 5 evaluated portfolios are to provide 1 MW of power for parts of 3 key buildings on the campus supporting the critical operations. All portfolios considered in this demonstration are composed of both conventional and renewable energy sources and technologies. Portfolio X_{01} contains passive solar technologies and backup technologies that rely largely on natural gas. Passive solar lighting increases energy efficiency. Portfolio X_{02} consists of solar photovoltaic (PV) panels positioned on 2 buildings, a microgrid, and diesel generators. Portfolio X_{02} has the highest dependence on foreign oil. The PV panels offset emissions and fossil fuel reliance. Portfolio X_{03} consists of wind turbines, biomass and waste energy conversion technologies, and coal energy technologies. Coal lessens the reliance on foreign energies. Portfolio X_{04} has the highest composition of conventional energies. Diesel and nuclear sources meet a large percentage of additional energy demand, whereas fuel cells provide additional backup and natural lightning reduces energy consumption. Portfolio X_{05} consists of a nuclear microturbine and a smaller portion of energy provided from biomass conversion supplements this portfolio. Otherwise, energy demand in this portfolio is met from the public grid.

Six criteria have been set forth to evaluate the benefits of each portfolio. The indexed criteria are: z_1 Energy continuity, z_2 Energy availability, z_3 Foreign inputs, z_4 Renewable sources and/or environmental impacts, z_5 System vulnerability, and z_6 Innovation. The first criterion z_1 is concerned with operational continuity and minimizing short-term supply disruptions. Means of scoring well in this criterion are to

increase backup power supplies and reduce dependence on the public grid. This objective is critical for daily mission or operational success. Portfolio X_{02} has the highest rating in this criterion because significant backup energy comes from diesel generators and the microgrid provides islanding capabilities.

The second criterion z_2 is concerned with ensuring that energy sources are available over the entire time domain. Criterion z_3 is concerned with decreasing the dependence on foreign energy products, specifically foreign oil. Portfolio X_{03} is the best-performing portfolio in this criterion. Criterion z_4 is concerned with reducing emissions and harmful energy byproducts and increasing the use of renewable energy sources. Criterion z_5 is concerned with the vulnerability of key buildings and energy supply systems from attacks and other failures and catastrophes. Decentralized energy sources help safeguard against attacks, but vulnerability to extreme weather and other events is also considered. Criterion z_6 is concerned with increasing investment and research in the advancement of energy technologies.

Table 1 provides the baseline pairwise comparison matrix P_Z for the 6 criteria under the baseline scenario s_0 , which does not assume the dominant presence of a future influential scenario. This matrix will be adjusted according to the scenario assumptions. The corresponding derived baseline weights for each criteria z_1 through z_6 are .31, .31, .11, .11, .11, .05, respectively. Table 2 displays the assessment scores of the 5 portfolios within each criterion. The criteria are listed along the left column and the portfolios across the top row. These assessment scores are derived from AHP comparison matrices using the eigenvector approach of the AHP. The matrices or calculations are not shown for brevity purposes. A baseline composite score is then calculated by combining the weights for the criteria with the assessment scores of the portfolios within each criterion.

Defining and incorporating future scenarios

Five scenarios are constructed to study the robustness of the portfolios:

- 1) s_1 : Oil and gas remaining available with low price volatility
- 2) s_2 : High growth and commercialization of renewable technology, high national economic growth, aggressive public investment in fuel cell technologies
- 3) s_3 : Increased volatility in oil and gas prices and supply, increased national demand for domestic energy sources
- 4) s_4 : Large emissions tax, high environmental movements
- 5) s_5 : Deterioration in geopolitics

Table 1. Baseline pairwise comparison matrix P_Z for the criteria

	z_1	z_2	z_3	z_4	z_5	z_6
z_1	1	1	3	3	3	5
z_2	1	1	3	3	3	5
z_3	1/3	1/3	1	1	1	3
z_4	1/3	1/3	1	1	1	3
z_5	1/3	1/3	1	1	1	3
z_6	1/5	1/5	1/3	1/3	1/3	1

Table 2. Assessment scores of the portfolios within each criterion (not overall scores)

Criteria	Portfolios				
	X_{01}	X_{02}	X_{03}	X_{04}	X_{05}
z_1	0.26	0.52	0.03	0.12	0.07
z_2	0.36	0.13	0.40	0.05	0.07
z_3	0.20	0.04	0.57	0.07	0.13
z_4	0.14	0.07	0.45	0.05	0.29
z_5	0.30	0.47	0.15	0.04	0.04
z_6	0.03	0.06	0.51	0.13	0.26

In the demonstration, these scores are not adjusted within each scenario.

The conditions and scenarios are gathered from various sources (Nakićenović 2000; Mintzer et al. 2003; World Energy Council 2007; United Nations 2008).

Some scenarios such as the first scenario have only 1 condition, that is, oil and gas remain available and cost-effective. Some scenarios such as s_2 express optimism in the growth of alternative energies. Others such as s_5 portray a more pessimistic future. Table 3 provides the different shifts in preference of the criteria for each scenario. Many scenarios in practice should require only a few adjustments to the baseline model. When a scenario requires many adjustments (i.e., tends to change the decision maker's preference structure significantly), it may be warranted to re-elicite all of the criteria comparisons for that scenario only.

For example, given the scenario s_1 , it is judged that the need to reduce foreign oil is not as important as previously concluded in the baseline scenario. All other criteria are judged as important (No Change). The matrix entry where this scenario and criterion meet is therefore Major Decrease. The pairwise matrix entries of the criteria are adjusted using the adjustment function h and the approach described earlier in the section *Efficient Incorporation of Scenarios to the Decision Model*, under *Multiple Criteria Decision Setting With Scenario Analysis*. Table 4 displays the new pairwise comparison matrix for s_1 . New criteria comparison matrices are similarly derived through adjustment for scenarios s_2 through s_5 .

The comparison matrices for the portfolios within each criterion are not changed for the scenarios in this demonstration. Changing only the criteria weights can be sufficient to reflect changes in preference for each long-term scenario (Parnell et al. 1999). The logic is that the portfolios that are best within each criterion in the baseline scenario are still best in the other scenarios. These preferences are preserved and that preferences among criteria are more likely to change in long-term planning for energy and environmental security. If this were not the case for a criterion given a scenario, and the performances of the portfolios were to change in that criterion, that individual matrix alone would be adjusted.

The demonstration illustrates the efficiency of the new approach. With the approach outlined herein, only 10 adjustment elicitation (Table 3, e.g., significant increase, significant decrease) were made to update the baseline model for all of the 5 scenarios other than the baseline scenario.

Table 3. Additional input of the 5 considered scenarios listed across the top row

Criteria	Scenarios				
	s_1	s_2	s_3	s_4	s_5
z_1	—	—	—	—	—
z_2	—	Minor decrease	Minor increase	—	Major increase
z_3	Major decrease	—	Major increase	—	Major increase
z_4	—	Major increase	—	Major increase	—
z_5	—	—	—	—	—
z_6	—	Major increase	—	Major increase	—

This input adjusts the baseline preference level of the 6 criteria along the left column. The inputs are restricted to Major Increase, Minor Increase, No change (dash), Minor Decrease, and Major Decrease.

Completely reconstructing the criteria comparison matrix for the 5 scenarios would require 75 total comparisons. This is because constructing the baseline model for the 6 criteria required fifteen pairwise comparisons ($5 + 4 + 3 + 2 + 1$). Seventy-five [$5(5 + 4 + 3 + 2 + 1)$] additional criteria comparisons would have been needed in this demonstration if the criteria comparison matrix were completely reconstructed per scenario. Using the new criteria weights and the previous assessments of the portfolios within the criteria, the portfolios can be scored and ranked for each scenario.

Results for prioritizing the energy and environmental security alternatives

Table 5 provides the composite scores and corresponding inter-scenario rankings for the portfolios under the baseline scenario and the 5 other scenarios. Portfolio X_{03} , with its high percentage of renewable and domestic energy sources and technologies, is the highest-performing portfolio in all but 1 considered scenario, s_1 (i.e., oil and gas remain available with low price volatility). Portfolio X_{02} is the highest-performing in scenario s_1 , as reducing foreign energies is not as important (X_{02} is the worst among all portfolios at reducing foreign oil). For Portfolio X_{03} , the scenario s_1 is viewed as disruptive, although the difference between the scores for X_{02} and X_{03} is small.

Whereas s_2 and s_4 adjust the baseline criteria comparison matrix in different ways, the scores and rankings of the

portfolios are similar. Scenarios s_2 and s_4 produce nearly the same ranking of alternatives. We seek to understand the performance of the portfolios relative to one another; additional insight is whether the scenarios present opportunities or vulnerabilities to the individual scores of each portfolio.

For example, portfolio X_{02} has a higher score in the baseline scenario s_0 and s_1 than in the other scenarios. Thus, the other scenarios s_2 through s_5 represent vulnerabilities to the individual performance of this portfolio. Conversely, scenarios s_2 and s_4 represent attractive scenarios for portfolio X_{05} , as the score improves when considering scenarios in addition to the baseline scenario.

Figure 2 displays the baseline score and range of scores for each portfolio. Figure 3 shows the baseline ranking and range of rankings for each portfolio. The diamonds indicate the baseline scenario. Portfolio X_{03} is robust across the scenarios. A small overlap in the scores for portfolios X_{02} and X_{03} can be seen in Figure 1. This overlap is responsible for the range bar for portfolio X_{03} extending below the diamond in Figure 3 to the second ranking position. Scenario s_1 is the most influential in the sense that it is the only scenario to upset X_{03} from being the top prioritized portfolio. Further directed engineering and modeling efforts with consideration of scenario s_1 are needed to confirm that X_{03} is an acceptable option in terms of all tradeoffs.

Table 5. Composite scores (no parentheses) and corresponding interscenario rankings (parentheses) of the 5 portfolios considered under all scenarios

Scenarios	Portfolios				
	X_{01}	X_{02}	X_{03}	X_{04}	X_{05}
s_0	0.27 (2)	0.27 (2)	0.29 (1)	0.08 (5)	0.11 (4)
s_1	0.27 (2)	0.28 (1)	0.27 (2)	0.08 (5)	0.11 (4)
s_2	0.18 (3)	0.18 (3)	0.37 (1)	0.08 (5)	0.20 (2)
s_3	0.26 (2)	0.17 (3)	0.39 (1)	0.07 (5)	0.11 (4)
s_4	0.19 (2)	0.17 (4)	0.37 (1)	0.07 (5)	0.19 (2)
s_5	0.28 (2)	0.17 (3)	0.38 (1)	0.07 (5)	0.10 (4)

Table 4. s_1 pairwise comparison matrix $P_{Z,1}$ for the criteria

	z_1	z_2	z_3	z_4	z_5	z_6
z_1	1	1	7	3	3	5
z_2	1	1	7	3	3	5
z_3	1/7	1/7	1	1/5	1/5	1/3
z_4	1/3	1/3	5	1	1	3
z_5	1/3	1/3	5	1	1	3
z_6	1/5	1/5	3	1/3	1/3	1

This matrix was generated by adjusting the baseline comparison matrix P_Z .

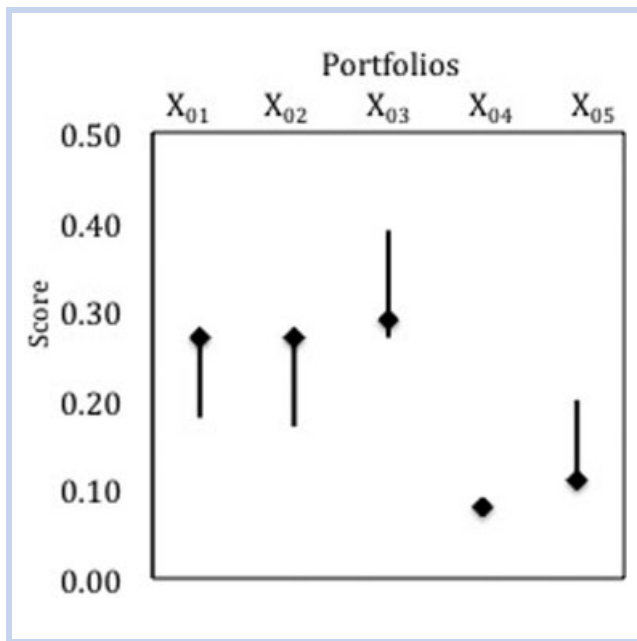


Figure 2. Ranges of portfolio scores under the considered scenarios. Diamonds represent baseline scores; range bars represent highest and lowest scores of portfolios across the scenarios.

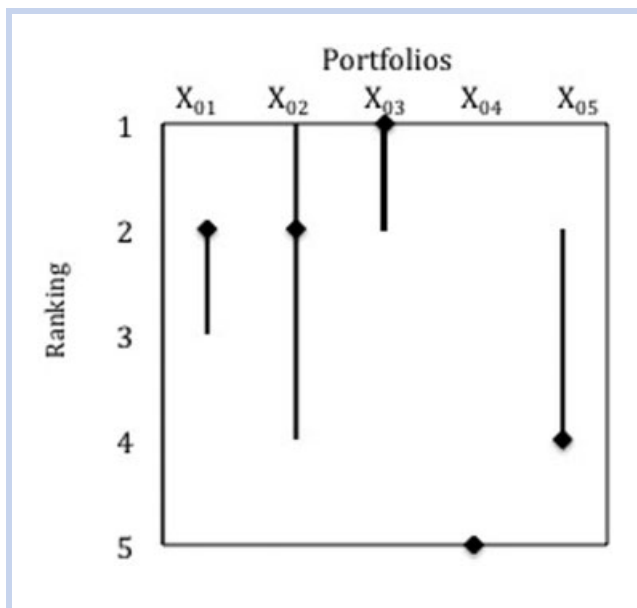


Figure 3. Ranges of portfolio rankings under the considered scenarios. Diamonds represent baseline scenarios; range bars represent highest and lowest rankings of portfolios across the scenarios.

DISCUSSION AND CONCLUSIONS

The integration of scenario analysis and MCDA framework proposed allows for the selection of robust investment for military and industrial facilities affected by short-term and long-term implications described by future scenarios. This approach builds on previous attempts to combine scenario analysis with MCDA and introduces a methodological innovation for distinguishing robust portfolios and the most relevant scenarios via adjustments of preferences in a formal MCDA model.

The problem is efficiently framed by asking stakeholders which criteria are more important or less important and whether the adjustment is to a small or large degree. This additional input is standard for each scenario, allowing for a systematic comparison and prioritization across scenarios. Once critical scenarios are known, additional modeling and investigative resources can be used to focus further investigation.

Unlike other models and rules in decision analysis, this approach does not always select a unique investment portfolio. It can, however, prioritize a subset of portfolios to focus additional resources and negotiation. The approach allows for a plurality of expert and stakeholder views of future scenarios. Multiple stakeholders can adjust the same model. In this case, each scenario can represent the view of an individual stakeholder or organization, leading to nonconsensus preferences for the criteria set. If this approach is implemented into software, it can be used as a negotiation or moderator tool. The approach can guide the negotiation process toward scenarios for which investors and stakeholders may be most effective to build consensus and understanding. In negotiation in a strategy workshop, MCDA tools are particularly effective when they can address uncertainties about both the future settings and organizational ideals (Montibeller and Franco 2010).

One way to deal with scenario uncertainty is traditional sensitivity analysis (Chatzimouratidis and Pilavachi 2009b) that varies specific parameters of a model to understand how the model output changes. Although sensitivity analysis can help characterize the robustness of investments, it is ill-suited to link scenarios to the prioritization and also to support of negotiation of multidisciplinary experts.

The present work uses AHP as an example to illustrate the efficient adjustment of stakeholder preferences by scenarios. Despite theoretical controversies documented in the literature, AHP has been found to be a practical tool for structuring multiple criteria decision problems and evaluating energy decision alternatives. The demonstration incorporated only a single hierarchical level of criteria. Incorporating multiple hierarchical levels of criteria, subcriteria, and portfolios along with quantification of the hierarchical effects of scenarios is recommended for future research efforts and applications. We used the approach to perform a preliminary benefits analysis and to describe the detailed cost analysis incorporating emergent conditions as a separate component in the decision process. Future research is also needed to integrate both analyses.

The example described does not demonstrate significant preference intransitivities, and the scenario adjustments do not introduce new intransitivities. In the demonstration, the consistency index for the baseline matrix (Table 1) is 0.012, which is below the recommended threshold of 0.10 (Saaty 1990). The consistency indexes for scenarios s_1 through s_5 are 0.031, 0.012, 0.031, 0.012, and 0.051, respectively. Although these did change, they are still below the threshold. Future research is needed to address how this method will deal with baseline intransitivities and when, if ever, the scenario adjustments will introduce new intransitivities.

Selecting energy and environmental alternatives for an industrial or military installation challenges multiple stakeholders to consider a spectrum of long-term and very near-term time horizons. The multiple conflicting objectives and agendas require the assimilation of multiple preferences and

perspectives. Although this demonstration was small and illustrative, a real application could increase the order of the decision space as well as scenario and stakeholder considerations. By building on the previous integrations of scenarios analysis with MCDA tools, we hope to inspire future efforts that seek to reduce the elicitation burden and incorporate multiple stakeholder perspectives.

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